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NUCLEAR ASTROPHYSICS AWAY FROM STABILITY

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Abstract

Explosive astrophysical environments invariably lead to the production of nuclei away from stability. An understanding of the dynamics and nucleosynthesis in such environments is inextricably coupled to an understanding of the properties of the synthesized nuclei. In this talk a review is presented of the basic explosive nucleosynthesis mechanisms (s-process, r-process, n-process, p-process, and rp-process). Specific stellar model calculations are discussed and a summary of the pertinent nuclear data is presented. Possible experiments and nuclear-model calculations are suggested that could facilitate a better understanding of the astrophysical scenarios.

Introduction

Even after several decades of research [BUR57] into the mechanisms by which the elements are synthesized in stars, it is still often true that the degree to which an astrophysical environment can be understood is limited by the degree to which the underlying microscopic input nuclear physics data have been measured and understood. As new and more exotic high-temperature astronomical environments have been discovered and modeled (and as observations and models for more familiar objects have been refined) the needs for more and better data for nuclei away from stability have increased. In this brief overview, we discuss a few of the explosive astrophysical environments which are currently of interest and some of their required input nuclear data.

We begin with a discussion of the poorly understood mechanisms for heavy-element nucleosynthesis and some of our efforts to understand these environments. Then we turn to a discussion of the exotic environments for hot hydrogen burning and some of our experimental and theoretical efforts to obtain the associated nuclear data.

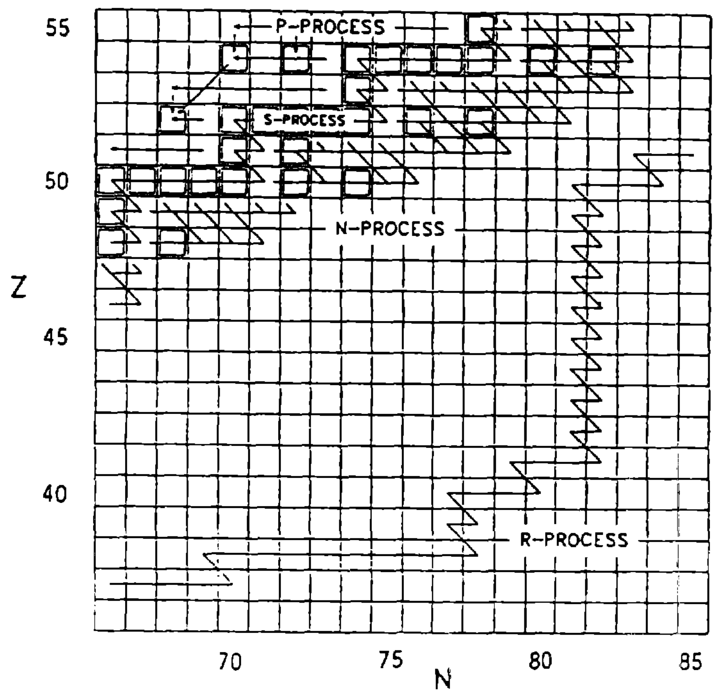

Fig. 1 The mechanisms for heavy-element nucleosynthesis drawn as lines representing the dominant isotopes produced during the processes [MAT85].

Heavy-Element Nucleosynthesis

Most nuclides with $A \gtrsim 70$ are synthesized by neutron capture. Figure 1 is from a recent review article [MAT85] on the various stellar processes for neutron capture nucleosynthesis. For the most part, these processes correspond to different time scales. The s-process describes neutron capture on a slow time scale compared with typical beta-decay lifetimes near the line of stability, and thus leads to the formation of a continuous chain of stable heavy elements from the iron group to ^{209}Bi. The r-process, on the other hand, corresponds to neutron capture on a time scale which is rapid compared with beta-decay lifetimes. In the limit of high neutron density, this process appears as a chain of isotopes for each element which represents the point of $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium far from stability. The n-process is what actually seems to be predicted by most stellar models [MAT85] for either the r-process or s-process, i.e. a competition between beta decay and neutron capture which can not be treated with the same mathematical simplicity as in the classical s-process and r-process [MAT85, SEE65]. The p-process is a somewhat less frequent process (as evidenced in abundances) which probably is the result of photodisintegration reactions in high-temperature [WOO78] or high-electron-density [HAR78] regimes.

The s-Process

Figure 2 is from some of our recent studies [MAT84a, MAT84b, HOW85] of the details of s-process nucleosynthesis in the framework of stellar models which produce neutrons by a $^{22}Ne(\alpha,n)^{25}Mg$ reaction during sequential thermal pulses in a helium-burning shell [IBE77]. What is plotted is the σN curve (neutron capture cross section times abundance) for stable isotopes along the chain of elements which are produced in the s-process. This calculation corresponds roughly to the conditions thought to exist in the interior of a 7 $M_{\odot}$ red-giant star on the asymptotic giant branch. Stars in this phase of evolution are unstable to a thermonuclear runaway of the helium-burning shell. In the explosive environment of one of these thermal pulses the neutron densities can become so high that successive neutron captures can occur out to nuclei well away from stability. Furthermore, the temperatures become so high ($T \sim 3x10^8K$) that the Boltzmann population of nuclear excited states can lead to dramatic changes of the neutron-capture and beta-decay rates.

In a classical s-process [MAT85] (low neutron density) Fig. 2 would be a smooth curve. However, as variations in the neutron density and temperature are taken into account, a structure emerges due to branch points, i.e., unstable nuclei with competing neutron-capture and beta-decay rates.

Thus, in order to understand such environments it is necessary to calculate complete network of the competitions between neutron capture and beta decay as well as their corrections for the thermal population of excited states. With regard to this latter correction it is particularly important to know the low-energy level structure of nuclei away from stability. This structure will affect the beta decay properties differently from the neutron capture properties. In a separate contribution to this conference, [TAK85] we will discuss the corrections for beta decay. Basically this becomes important if a low-lying excited state can undergo a Gamow-Teller allowed decay. The

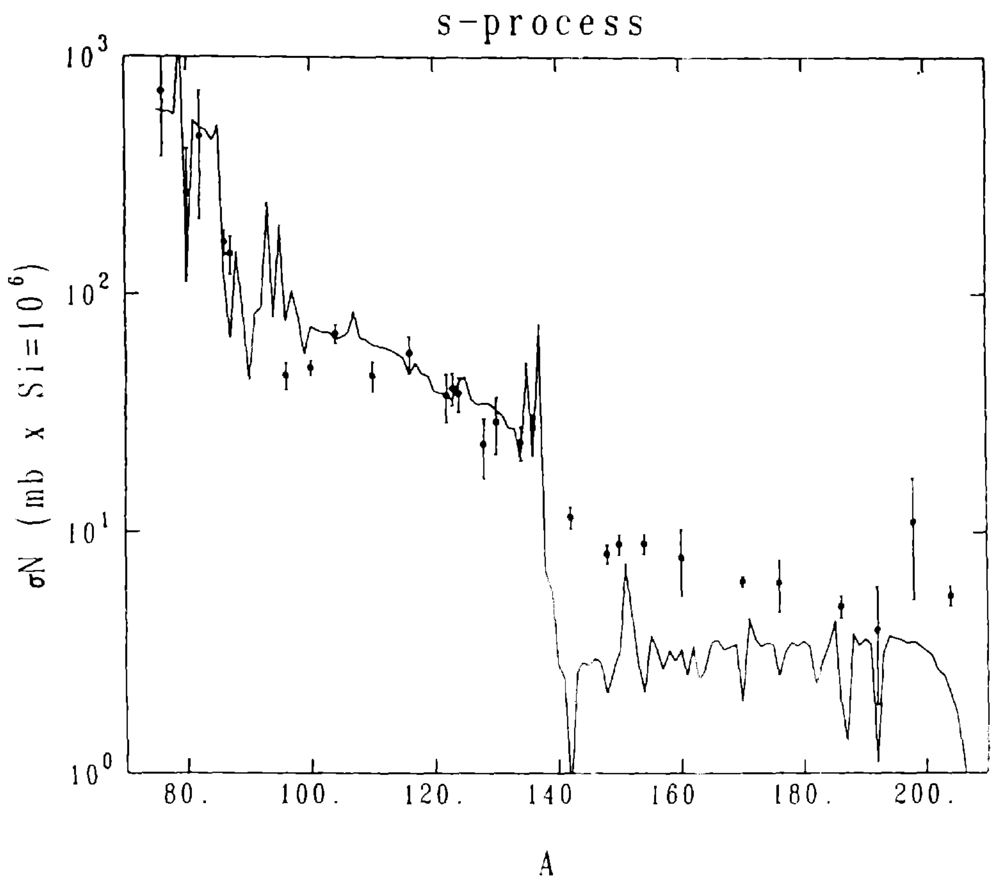

Figure 2 The σN curve calculated [MAT84ab, HOW85] in the framework of stellar models [IBE77] for the s-process in thermally-pulsing red-giant stars.

corrections to the cross sections become the greatest for low-lying states with considerably different spins.

Figure 3 is an illustration of some calculated [HOM76] thermal correction factors for ground-state neutron-capture cross sections for a number of isotopes near the line of stability. From this figure it is clear that these correction factors can be significant. For the benefit of anyone who might like to attack this problem. Table I summarizes some of what we consider to be the most important quantities to better refine as input to the s-process.

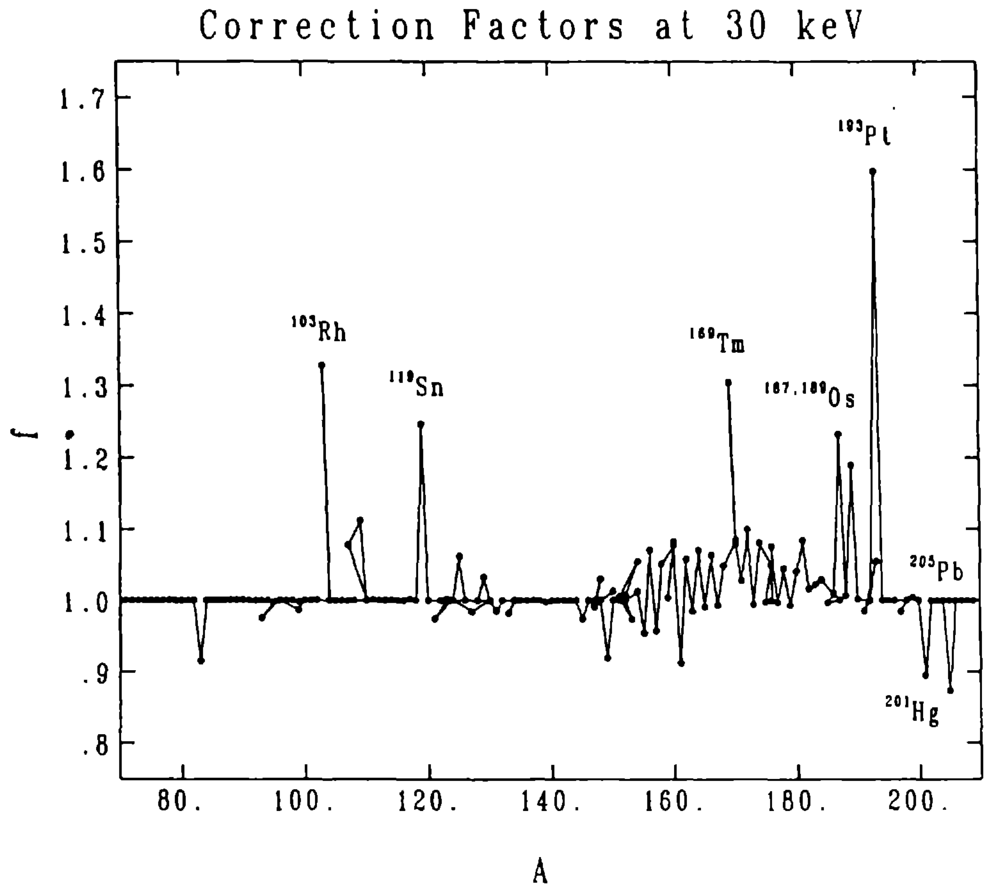

Figure 3 Correction factors, f, for the neutron-capture cross section for various isotopes due to the thermal population of excited states at stellar temperatures (from [HOW76]). Isotopes with f > 10% are labeled.

TABLE I Some nuclear data which would be most useful for s-process nucleosynthesis.

1. Stable nuclei for which the neutron capture cross section has not been measured; ^{66}Zn, ^{72,73}Ge, ^{77}Se, ^{99}Ru.

2. Important unstable nuclei for which the neutron capture cross section has not been measured; ^{79}Se, ^{85}Kr, ^{107}Pd, ^{147}Pm, ^{151}Sm, ^{166}Ho, ^{186}Re, ^{192}Ir, ^{205}Pb.

3. Nuclei with large thermal correction factors for the ground-state neutron capture cross sections; ^{103}Rh, ^{119}Sn, ^{169}Tm, ^{187,189}Os, ^{193}Pt, ^{201}Hg, ^{205}Pb.

4. Branch points with large corrections for thermally-enhanced beta decay; ^{60}Co, ^{63}Ni, ^{79}Se, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{134}Cs, ^{151}Sm, ^{152,154,155}Eu, ^{160}Tb, ^{163}Dy, ^{163}Ho, ^{176}Lu, ^{181,182}Hf, ^{187}Re, ^{187}Os, ^{204,205}Tl.

The r-process

The required nuclear input data for the r-process are summarized in detail elsewhere [MAT83a, MAT85]. The astrophysical site for the r-process is still not known, although a number of promising possibilities have been proposed [MAT85, SEE65, BLA81, THI79, COW82]. Basically there are two fundamental time scales which must be determined from better nuclear input data before the ambiguity surrounding the r-process site can be resolved. One is just how high the neutron density must be to reproduce the r-process abundances. This quantity depends on the ratios of neutron-capture to beta-decay rates. For some scenarios [BLA81, COW82, CAM83] it is possible to reproduce the observed r-process abundances without reaching (n,γ) equilibrium. Then the abundance peaks will largely be determined by the neutron capture cross sections away from stability as demonstrated in [CAM83].

The cross sections away from stability have for the most part been estimated from global Hauser-Feshbach calculations [HOM76] although near neutron closed shells direct radiative capture may be more appropriate [MAT83b]. Along this line we are currently investigating the viability of a new statistical formalism [VER84] based on a random matrix approach to describe the statistical fluctuations. This formalism has the advantage that it goes to the correct limit when the number of channels becomes small. In any of these calculations it becomes extremely important to know the level structure for low-lying states (which may have significant gamma channels) and states near 1-3 MeV excitation which may have resonance contributions for nuclei away from stability. Some progress in this latter regard has been made [KRA83, WIE84] by utilizing data from delayed neutron emission to identify some of the states populated in the inverse neutron-capture reaction.

If (n,γ) equilibrium is achieved, then the abundances will be determined by the beta-decay rates of unmeasured nuclei far from stability. Although some progress has been made [KLA81, TAK85] in shell model calculations of these rates, further studies are warranted.

The second quantity which must be determined for the r-process is the dynamical time scale during which the neutron density must remain high in order to produce the actinides (which can not be produced by the s-process due to alpha particle decay at ^{210}Bi). This quantity depends on the sum of the neutron-capture and beta-decay lifetimes as one moves away from stability. Essentially, the r-process must live long enough for nuclei to capture out to far from stability and then beta decay up to the mass numbers of the actinides. This places a severe constraint on dynamical processes such as shock-driven explosive helium burning during a supernova [BLA81, KLA81]. At present, it appears that the calculated beta-decay rates may be too slow [COW85]. Clearly, more refined determinations of neutron-capture cross sections and beta-decay rates are desired before the astrophysical site for the r-process can be determined.

p-Process

The p-process is responsible for the production of a number of neutron deficient nuclei. The astrophysical site for the p-process is not well established, but the most viable models at the present time [WOO78, HAR78] attribute this process in one way or another to photodisintegration reactions of heavier more abundant species. In [WOO78] the photodisintegration is thought to occur in the high temperature regions after passage of a supernova shock. In [HAR78] it has been suggested that that energetic photons ($\sim$19MeV) from the $^{3}H(p,\gamma)^{4}He$ reaction may induce photonuclear reactions before the photons are thermalized. In both of these cases it is desirable to know photonuclear (γ,n), (γ,p), and (γ,α) rates neutron deficient nuclei.

Hot Hydrogen Burning

For a host of astrophysical environments (e.g. novae, supernovae, supermassive stars, accreting neutron stars, and dense inhomogeneous cosmologies [WAL81]) hydrogen burning may occur at temperatures far in excess of the temperatures ($10^{6}<T<10^{8}K$) associated with normal main-sequence stellar evolution (see Fig. 4). In such environments, charged-particle reaction data for unstable nuclei become important.

Almost any time there is thermonuclear hydrogen burning, there is a possibility for proton reactions on unstable nuclei. Well known examples are the $^{7}Be(p,\gamma)^{8}B$ reaction in the sun (which is a particularly important link in the chain of reactions leading to the

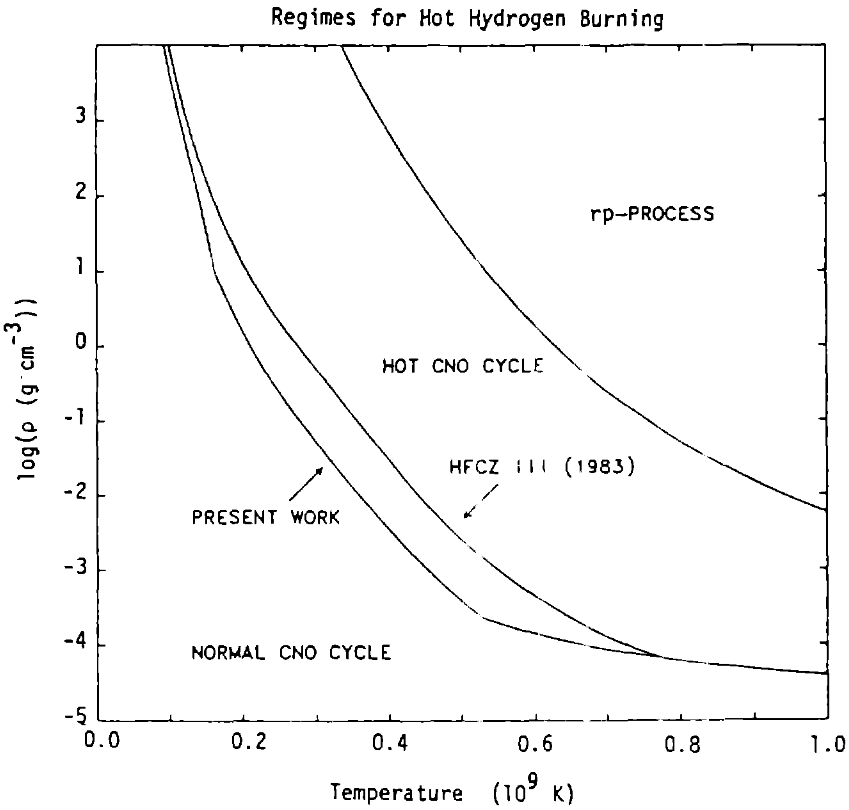

Figure 4 Regions of the density vs. temperature plane in which the various hydrogen-burning processes are dominant [MAT84c]. The normal CNO cycle occurs in stars slightly larger than the sun. The hot (beta-limited) CNO cycle is particularly important in supermassive stars. The rp-process is important during the thermonuclear runaways on accreting neutron stars which may be the source of X-ray bursts.

production of solar neutrinos detectable in the ^{37}Cl experiment [BAH78]) the ^{22}Na(p,γ)^{23}Mg reaction in the Ne-Na cycle, and the reactions of ^{26}Al in the Mg-Al cycle. When the temperatures are high, a few other reaction rates also become important. For $T \gtrsim 2 \times 10^8$K the waiting point for the normal hydrogen-burning CNO cycle shifts [MAT84c] from ^{14}N to ^{13}N, and then, via the ^{13}N(p,γ)^{14}O reaction, shifts to the production of ^{14}O and ^{15}O. This is the hot (beta-limited) CNO cycle [WAL81], which is particularly significant in the evolution of supermassive ($M > 10^4 M_{\odot}$) stars [FUL85]. This hot hydrogen-burning scenario may also come into play on accreting white dwarfs [WAL81] and in the formation of x-ray bursts from accreting neutron stars [AYA82, WOO83].

As the temperature and density continue to increase, the $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{15}O(\alpha,p)^{18}F$ reactions lead to break out from the CNO cycle to a process of rapid proton capture (rp-process) which involves sequential proton captures out to the proton drip line or until the Coulomb barrier becomes too large. Each of these transitions to higher-temperature reactions lead to orders-of-magnitude increases in the rates of energy production. Thus, in addition to effects on nucleosynthesis, the dynamics of the various high temperature environments are intimately coupled to the cross sections for proton and alpha-particle capture reactions on unstable nuclei. In a few cases [WAL81] even the question of whether the next proton or aphha capture leads to a bound nuclear state can have a dramatic effect on the evolution of the environment.

Essentially two different approaches have been attempted to supply the necessary data. The most straightforward approach (which we will call the finesse approach) is to utilize nuclear data obtained by conventional means combined with a model for the nuclear structure and reaction mechanisms to derive the desired input datum. This has been done for the $^{13}N(p,\gamma)^{14}O$ reaction [MAT84c, CHU85, LAN85], the ^{14}O, ^{15}O, and ^{19}Ne reactions [WIE85], and heavier nuclei [SCH84]. This approach has been quite productive since many of the reactions of interest are probably dominated by one or a few resonances whose radiative and particle widths can be inferred indirectly. There is still quite a bit that can be done with this approach, for example to better identify the energies and widths of the resonances of interest, particularly for nuclei far on the proton-rich side of stability which tend to become the waiting points for this process.

The other approach to obtain these data (which we will call the brute-force approach) is to produce a beam of radioactive heavy ions to be focused onto a target of hydrogen or ^4He (or in a few cases to do measurements on a radioactive target [FIL83]). The radioactive ion-beam brute-force approach is much more difficult but may provide more information. We have been involved in a modest effort [HAI83, MAT84d] to develop this technology along with a number of other labs [BOY80, NIT84, AUR85].

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